The Scientific Basis for Common Modeling Infrastructure

NOAA/CPO MAPP Seminar

V. Balaji

NOAA/GFDL and Princeton University

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Multi-model ensembles for climate projection

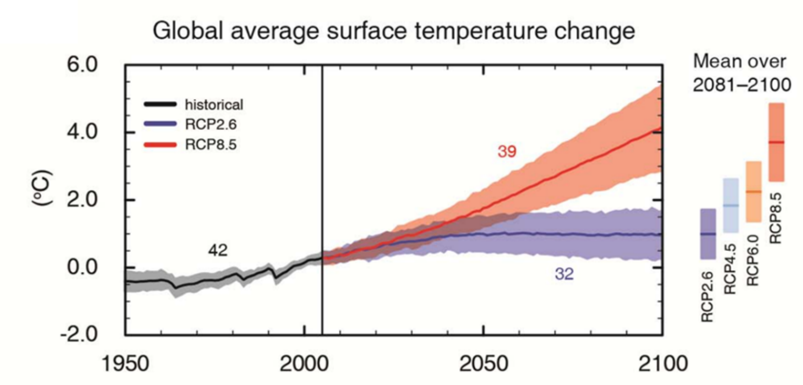


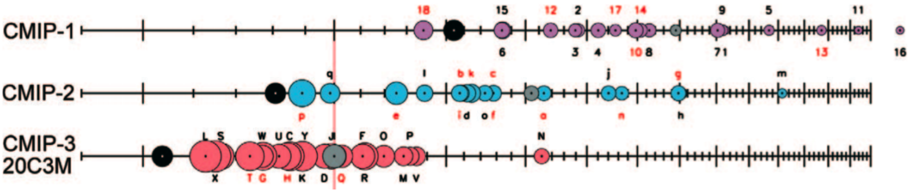
Figure SPM.7 from the IPCC AR5 Report.

NRC Recommendations on Common Model Infrastructure

The 2012 NRC Report "A National Strategy for Advancing Climate Modeling" (Google for URL...) made several recommendations:

- Structural uncertainty: key issue to be addressed with common modeling experiments: maintain model diversity while using common infrastructure to narrow the points of difference.
- Global data infrastructure as critical infrastructure for climate science: data interoperability, common software requirements.
- "Nurture" at least one unified weather-climate effort: NWP methods to address climate model biases; climate runs to address drift and conservation in weather models.
- Forum to promote shared infrastructure: identify key scientific challenges, design common experiments, set standards for data interoperability and shared software.

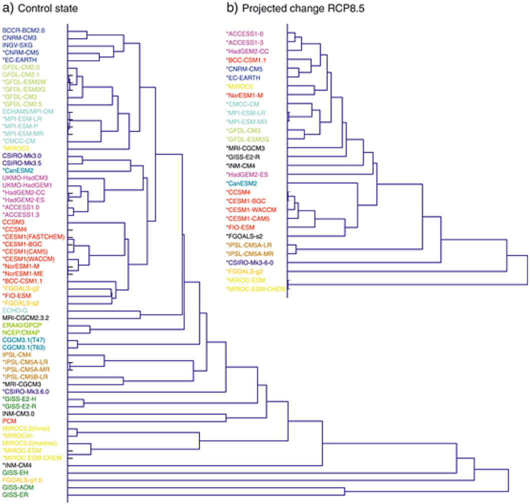
Multi-model ensembles to overcome "structural uncertainty"



Reichler and Kim (2008), Fig. 1: compare models' ability to simulate 20th century climate, over 3 generations of models.

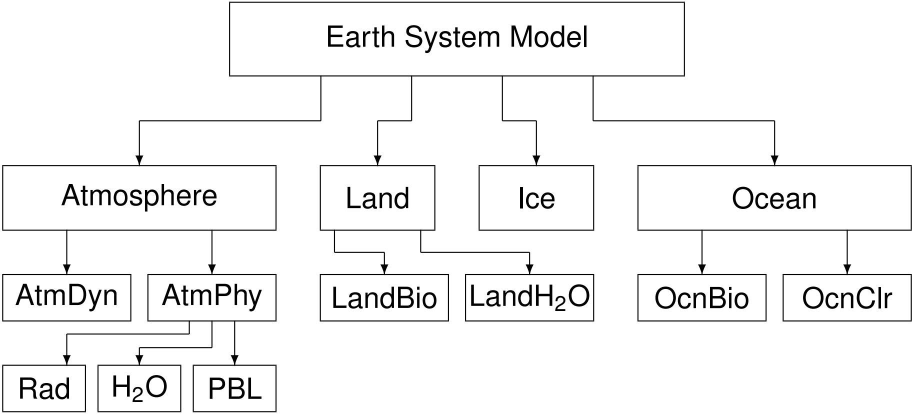
- Models are getting better over time.
- The ensemble average is better than any individual model.
- Improvements in understanding percolate quickly across the community.

Genealogy of climate models



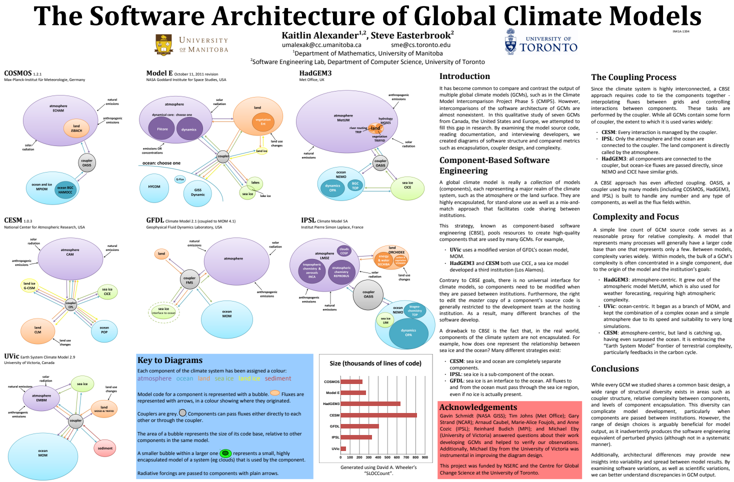
There is a close link between “genetic distance” and “phenotypic distance” across climate models (Fig. 1 from Knutti et al, GRL, 2013).

Earth System Model Architecture



Notional architecture of an Earth System Model. Different models may embody this differently in code.

Diversity of coupling architectures



The Software Architecture of Global Climate Models

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IN41A-1394

COSMOS 1.2.1
Max-Planck-Institut für Meteorologie, Germany

Model E October 11, 2011 revision
NASA Goddard Institute for Space Studies, USA

HadGEM3
Met Office, UK

CESM 1.0.3
National Center for Atmospheric Research, USA

GFDL Climate Model 2.1 (coupled to MOM 4.1)
Geophysical Fluid Dynamics Laboratory, USA

IPSL Climate Model 5A
Institut Pierre Simon Laplace, France

UVic Earth System Climate Model 2.9
University of Victoria, Canada

Key to Diagrams

Each component of the climate system has been assigned a colour:
atmosphere ocean land sea ice land ice sediment

Model code for a component is represented with a bubble. Fluxes are represented with arrows, in a colour showing where they originated.

Couplers are grey. Components can pass fluxes either directly to each other or through the coupler.

The area of a bubble represents the size of its code base, relative to other components in the same model.

A smaller bubble within a larger one represents a small, highly encapsulated model of a system (eg clouds) that is used by the component.

Radiative forcings are passed to components with plain arrows.

Size (thousands of lines of code)

Generated using David A. Wheeler's "SLOCCount".

Introduction

It has become common to compare and contrast the output of multiple global climate models (GCMs), such as in the Climate Model Intercomparison Project Phase 5 (CMIP5). However, intercomparisons of the software architecture of GCMs are almost nonexistent. In this qualitative study of seven GCMs from Canada, the United States and Europe, we attempted to fill this gap in research. By examining the model source code, reading documentation, and interviewing developers, we created diagrams of software structure and compared metrics such as encapsulation, coupler design, and complexity.

Component-Based Software Engineering

A global climate model is really a *collection* of models (components), each representing a major realm of the climate system, such as the atmosphere or the land surface. They are highly encapsulated, for stand-alone use as well as a mix-and-match approach that facilitates code sharing between institutions.

This strategy, known as component-based software engineering (CBSE), pools resources to create high-quality components that are used by many GCMs. For example,

- **UVic** uses a modified version of GFDL's ocean model, MOM.
- **HadGEM3** and **CESM** both use CICE, a sea ice model developed a third institution (Los Alamos).

Contrary to CBSE goals, there is no universal interface for climate models, so components need to be modified when they are passed between institutions. Furthermore, the right to edit the *master* copy of a component's source code is generally restricted to the development team at the hosting institution. As a result, many different branches of the software develop.

A drawback to CBSE is the fact that, in the real world, components of the climate system are not encapsulated. For example, how does one represent the relationship between sea ice and the ocean? Many different strategies exist:

- **CESM**: sea ice and ocean are completely separate components.
- **IPSL**: sea ice is a sub-component of the ocean.
- **GFDL**: sea ice is an interface to the ocean. All fluxes to and from the ocean must pass through the sea ice region, even if no ice is actually present.

Acknowledgements

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The Coupling Process

Since the climate system is highly interconnected, a CBSE approach requires code to tie the components together - interpolating fluxes between grids and controlling interactions between components. These tasks are performed by the coupler. While all GCMs contain some form of coupler, the extent to which it is used varies widely:

- **CESM**: Every interaction is managed by the coupler.
- **IPSL**: Only the atmosphere and the ocean are connected to the coupler. The land component is directly called by the atmosphere.
- **HadGEM3**: all components are connected to the coupler, but ocean-ice fluxes are passed directly, since NEMO and CICE have similar grids.

A CBSE approach has even affected coupling. OASIS, a coupler used by many models (including COSMOS, HadGEM3, and IPSL) is built to handle any number and any type of components, as well as the flux fields within.

Complexity and Focus

A simple line count of GCM source code serves as a reasonable proxy for relative complexity. A model that represents many processes will generally have a larger code base than one that represents only a few. Between models, complexity varies widely. Within models, the bulk of a GCM's complexity is often concentrated in a single component, due to the origin of the model and the institution's goals:

- **HadGEM3**: atmosphere-centric. It grew out of the atmospheric model MetUM, which is also used for weather forecasting, requiring high atmospheric complexity.
- **UVic**: ocean-centric. It began as a branch of MOM, and kept the combination of a complex ocean and a simple atmosphere due to its speed and suitability to very long simulations.
- **CESM**: atmosphere-centric, but land is catching up, having even surpassed the ocean. It is embracing the "Earth System Model" frontier of terrestrial complexity, particularly feedbacks in the carbon cycle.

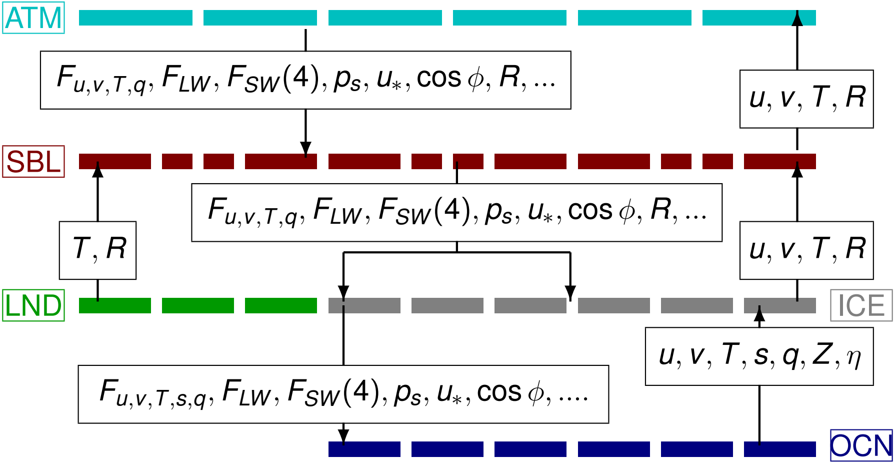
Conclusions

While every GCM we studied shares a common basic design, a wide range of structural diversity exists in areas such as coupler structure, relative complexity between components, and levels of component encapsulation. This diversity can complicate model development, particularly when components are passed between institutions. However, the range of design choices is arguably beneficial for model output, as it inadvertently produces the software engineering equivalent of perturbed physics (although not in a systematic manner).

Additionally, architectural differences may provide new insights into variability and spread between model results. By examining software variations, as well as scientific variations, we can better understand discrepancies in GCM output.

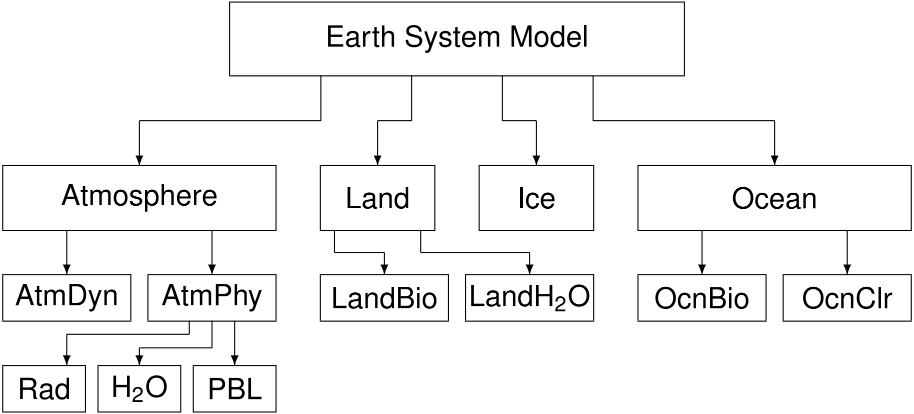
Alexander and Easterbrook, AGU 2011.

Physical architecture is often model-specific


ATM
$F_{u,v,T,q}, F_{LW}, F_{SW}(4), p_s, u_*, \cos\phi, R, ...$
u, v, T, R
SBL
T, R
$F_{u,v,T,q}, F_{LW}, F_{SW}(4), p_s, u_*, \cos\phi, R, ...$
u, v, T, R
LND
ICE
u, v, T, s, q, Z, η
$F_{u,v,T,s,q}, F_{LW}, F_{SW}(4), p_s, u_*, \cos\phi, ...$
OCN

FMS coupled architecture: fluxes down, state variables up, implicit vertical diffusion (*R* both and down and up).

Earth System Model Architecture



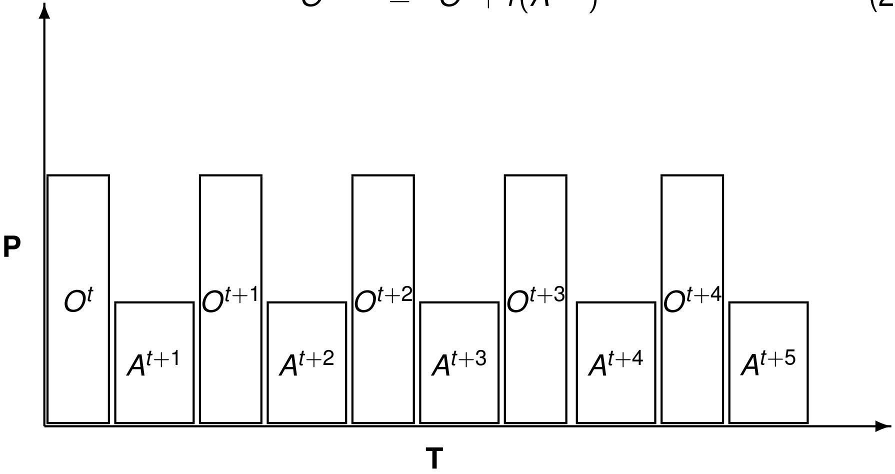
Extending component parallelism to $\mathcal{O}(10)$ requires a different physical architecture!

Serial coupling

Uses a forward-backward timestep for coupling.

$$A^{t+1} = A^t + f(O^t) \tag{1}$$

$$O^{t+1} = O^t + f(A^{t+1}) \tag{2}$$

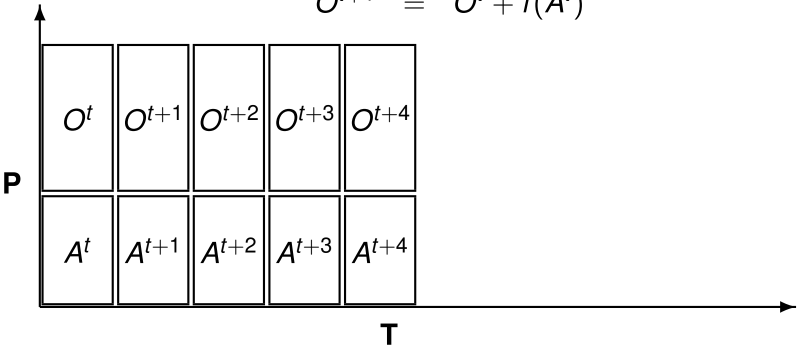


Concurrent coupling

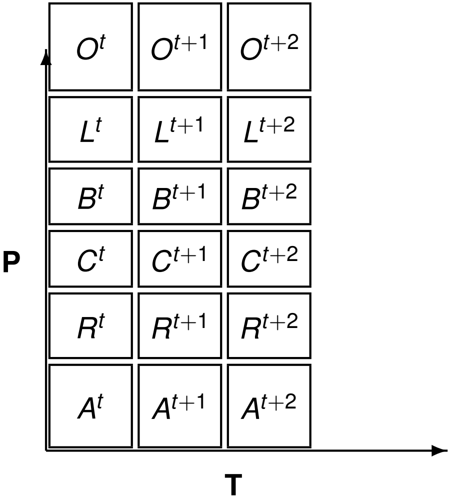
This uses a forward-only timestep for coupling. While formally this is unconditionally unstable, the system is strongly damped*. Answers vary with respect to serial coupling, as the ocean is now forced by atmospheric state from Δt ago.

$$A^{t+1} = A^t + f(O^t) \tag{3}$$

$$O^{t+1} = O^t + f(A^t) \tag{4}$$



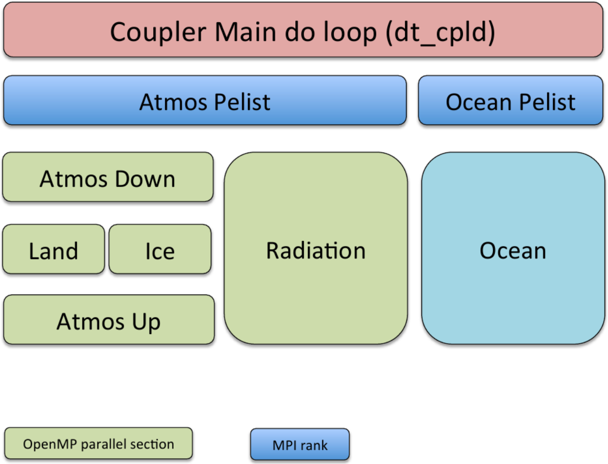
Massively concurrent coupling



O^t	O^{t+1}	O^{t+2}
L^t	L^{t+1}	L^{t+2}
B^t	B^{t+1}	B^{t+2}
C^t	C^{t+1}	C^{t+2}
R^t	R^{t+1}	R^{t+2}
A^t	A^{t+1}	A^{t+2}

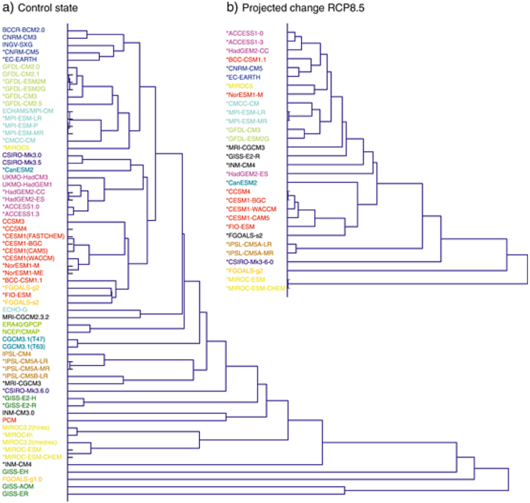
Components such as radiation, PBL, ocean biogeochemistry, each could run with its own grid, timestep, decomposition, even hardware. Coupler mediates state exchange.

Concurrent coupling: hybrid approach



Physics and radiation share memory. (Figure courtesy Rusty Benson, NOAA/GFDL).

Knutti et al, revisited



“Genetic health” in the modeling ecosystem? NRC Report: maintain diversity for structural uncertainty, reduce elsewhere.

Summary

- Sharing infrastructure is a hard problem, and not cost-free: should not be assumed to be just axiomatically a good idea.
- Should be done with a purpose: such as scientific reproducibility of simulations, making the process of setting up a MIP lightweight.
- Recognize the diversity of models, of coupling architectures (never say “plug and play”...!), and the value of this diversity.
- Interoperability and shared infrastructure has many aspects: common experimental protocols, common analytic methods, common documentation standards for data and data provenance, shared workflow, shared model components, shared technical layers. (ESDOC, ESGF, ESMF, ...)